Report No. NAWCADWAR-92021-50

HIGH POWER BLUE-GREEN β-BaB_2O_4 OPTICAL PARAMETRIC OSCILLATOR

Bruce P. Boczar
Mission and Avionics Technology Department (Code 5012)
NAVAL AIR WARFARE CENTER, AIRCRAFT DIVISION
Warminster, PA 18974-5000

Thomas W. Hamilton
AEROSPACE MASS PROPERTIES ANALYSIS, INC.
2640 Amy Drive
Norristown, PA 19403

NADC Tech. Info.

19970605 054

1 APRIL 1992

FINAL REPORT
Period Covering September 1988 to August 1991

Approved for Public Release; Distribution is Unlimited.

DTIC QUALITY INSPECTED 2

Prepared for
IR/IED (Code 01)
NAVAL AIR WARFARE CENTER, AIRCRAFT DIVISION
Warminster, PA 18974-5000

92001184

NOTICES

REPORT NUMBERING SYSTEM — The numbering of technical project reports issued by the Naval Air Warfare Center, Aircraft Division, Warminster is arranged for specific identification purposes. Each number consists of the Center acronym, the calendar year in which the number was assigned, the sequence number of the report within the specific calendar year, and the official 2-digit correspondence code of the Functional Department responsible for the report. For example: Report No. NAWCADWAR-92001-60 indicates the first Center report for the year 1992 and prepared by the Air Vehicle and Crew Systems Technology Department. The numerical codes are as follows:

CODE	OFFICE OR DEPARTMENT
00	Commanding Officer, NAWCADWAR
01	Technical Director, NAWCADWAR
05	Computer Department
10	AntiSubmarine Warfare Systems Department
20	Tactical Air Systems Department
30	Warfare Systems Analysis Department
50	Mission Avionics Technology Department
60	Air Vehicle & Crew Systems Technology Department
70	Systems & Software Technology Department
80	Engineering Support Group
90	Test & Evaluation Group

PRODUCT ENDORSEMENT — The discussion or instructions concerning commercial products herein do not constitute an endorsement by the Government nor do they convey or imply the license or right to use such products.

Reviewed By: ______________________ Date: 6/11/92
Branch Head

Reviewed By: K. J. Peter Date: 6/11/92
Division Head

Reviewed By: ______________________ Date: 6/11/92
Director/Deputy Director

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of Information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Airlington, VA 22202-4302, and to the Office of management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1 APRIL 1992

3. REPORT TYPE AND DATES COVERED
FINAL — Sept., 1988 – Aug., 1991

4. TITLE AND SUBTITLE
HIGH POWER BLUE-GREEN β-BaB_2O_4 OPTICAL PARAMETRIC OSCILLATOR

5. FUNDING NUMBERS

6. AUTHOR(S)
BRUCE P. BOCZAR (NAWCADWAR)
THOMAS W. HAMILTON (AMPAC)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Mission and Avionics Technology Department (Code 5012)
NAVAL AIR WARFARE CENTER, AIRCRAFT DIVISION
Warminster, PA 18974-5000
(Aerospace Mass Properties Analysis, Inc.
2640 Amy Dr., Norristown, PA 19403)

8. PERFORMING ORGANIZATION REPORT NUMBER
NAWCADWAR-92021-50

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
IR/IED (Code 01)
NAVAL AIR WARFARE CENTER, AIRCRAFT DIVISION
Warminster, PA 18974–5000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A high power, pulsed beta-barium borate optical parametric oscillator pumped by a frequency tripled Nd: YAG laser has been constructed and characterized. Antireflection coatings, oscillation thresholds, pump pulse duration, pulsewidth reduction, and spectral linewidths have been evaluated. Output pulse energies of 29 mj and an average power of 0.27 watts has been achieved at 480 nm.

14. SUBJECT TERMS
LASER RADAR, VISIBLE LASER SOURCES

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

CONTENTS

FIGURES

FIGURES (Continued)

ACKNOWLEDGMENT

The authors would like to thank Dean Guyer of STI Optronics for technical discussions.

INTRODUCTION

Optical parametric oscillators, (OPO's), have long been recognized as a source of tunable radiation. The basic device consists of a nonlinear material placed within an optical resonator. When the device is pumped by an intense laser beam, the radiation inside the cavity builds up from noise. The intracavity field continues to achieve gain from the pumping field and the oscillation threshold is achieved. The wavelengths that oscillate, (and that continue to receive gain), are governed by energy and momentum conservation constraints, (phase matching). The lack of suitable and durable nonlinear materials, however, has prevented the OPO from becoming a practical device. Recent material developments, such as urea, beta barium borate, and lithium triborate, have renewed the prospects of OPO's becoming useful and durable frequency agility devices, especially in the visible portion of the spectrum, [1-7].

An OPO optimized for blue-green output wavelengths and pumped by a frequency tripled Nd:YAG laser has been constructed and characterized. A variety of experimental conditions have been investigated. These include resonator variations, the use of antireflection coatings on the nonlinear crystals, variations of the pump pulse duration and insertion of intracavity etalons for spectral line narrowing of the output.

EXPERIMENTAL

The pump laser is an open frame Nd:YAG laser in an oscillator, (large mode; telescopic),/single pass amplifier configuration. The laser output is frequency doubled in a Type I beta barium borate, (BBO), crystal and frequency tripled in a Type II KD*P crystal. The laser is capable of generating up to 527, 254, and 140 mj/pulse at the fundamental, second harmonic, and third harmonic wavelengths, respectively. This corresponds to an energy conversion efficiency of 48% to the second harmonic and 27% to the third harmonic from the fundamental pulse energy. The laser repetition rate is variable from 0 to 10 Hz. The pulsewidth is selectable to either 10 or 15 ns, FWHM. The multi-transverse mode beam divergence was measured to be 1.4 mrad, full angle.

The nonlinear material used for the OPO in this study was beta barium borate, (BBO). Several uncoated samples were received from the People's Republic of China through various vendors. Several antireflection coated samples were obtained from Cleveland Crystals, Inc. The coating was a single layer MgF_2 coating and was specified to have a reflection of 0.75 % at 480 nm.

Figure 1 shows a calculated phase matching curve for a Type I BBO OPO pumped by a frequency tripled Nd:YAG laser at 354.7 nm. The Sellmeier equation used is of the form

$$n^2 = A + \left(B/(\lambda^2 + C)\right) + D\lambda^2 \qquad [1]$$

where λ is in microns and the coefficients are those published by Eimerl, et al, [8].

The uncoated BBO samples used were cut at an internal phase matching angle of 31.1°, as these were "off the shelf" samples. The coated samples

were cut at an internal phase matching angle of 30.0°, as these were customized pieces. All the crystals were cut for Type I phase matching, as this maximized the effective nonlinear coefficient. All of the crystals were nominally 9 mm long and had an aperture of 5 mm x 5 mm.

The OPO resonator is a plane-parallel resonator, 3 cm in length, operated in a straight thru pumping configuration. In addition, two nonlinear crystals were used for walkoff compensation, [9], resulting in a total gain length of 18 mm. Figure 2 shows the resonator mirror reflectance/transmission spectra. The OPO is optimized for signal outputs in the blue-green spectral region and is a singly resonant oscillator, (idler wavelength not shown in Figure 2). The OPO performance was evaluated both with and without a pump retroreflector. The pump retroreflector allows for gain in the reverse direction and hence a lower oscillation threshold and higher a conversion efficiency.

The harmonics of the Nd:YAG wavelengths were separated with a Pellin Brocca prism. The 354.7 nm pump beam was passed through a 2x reducing and collimating telescope yielding a spot size of 0.045 cm^2 and a full angle beam divergence of 0.74 mrad.

Results:

Photon conversion efficiencies were obtained with a Scientech Model 380101 calorimeter. The total output energy was measured and compared to the incident pump energy to obtain the photon conversion efficiency. The photon conversion efficiency was multiplied by 0.74 to obtain the energy conversion efficiency to 480 nm. The factor of 0.74 accounts for the fraction of the total output energy contained in the 480 nm signal wave and in the 1359 nm idler wave. The signal wave energies and energy conversion numbers

presented are slightly on the low side because the idler energy which escapes from the OPO in the backward direction has not been accounted for. In other words, the value of 0.74 slightly underestimates the signal-to-idler energy ratio in the forward traveling output beam. All the results presented have been corrected for the Fresnel losses due to a Schott GG400 glass filter which was used to remove any residual pump radiation from the output beam.

Figure 3 compares the energy conversion efficiency for OPO's in which AR coated and uncoated nonlinear crystals are used. The pump pulsewidth was 10 ns, FWHM, and was doubled passed through the OPO. As can be seen, the use of AR coated crystals dramatically improves OPO performance. An energy conversion efficiency of 27.3% and a photon conversion efficiency of 37.3% was obtained with an incident pump intensity of 153 MW/cm^2. Figure 4 shows the same data in terms of pump energy in vs signal energy out. Not only is the oscillation threshold reduced but the slope efficiency is increased when AR coated crystals are used. The slope efficiency is 33% and 45% for energy and photon conversion, respectively, when AR coated crystals are used.

Figures 5 and 6 compare the energy conversion efficiencies for a double pass pump configuration versus a single pass pump configuration for pump pulse durations of 10 ns and 15 ns , respectively. The main advantage of the double pass pump configuration is that the oscillation threshold of the OPO is lowered and hence higher conversion efficiencies are obtained at lower incident power densities. Also note that in comparing results between the 10 ns and 15 ns case, similar conversion efficiencies are obtained with comparable pump intensities, even though the fluence level and the pump level above threshold is higher for the longer pump pulse duration.

The oscillation threshold for the single pass pump configuration, for both values of the pump pulse duration, was calculated according to the model given by Brosnan and Byer, [10], and Komine, [3], and is expressed in terms of a threshold fluence, given by:

$$J_O = 1.064\, t_p G_o^{\,2} / kL^2 \qquad [2]$$

where

$$G_O = 1.34 \ln\left[e^f + (e^{2f} - 1)^{1/2}\right] \qquad [3]$$

and

$$f = (0.589 L_C / ct_p) \ln (P_{th} / P_{noise}) - 0.5 \ln (R) + 2a \qquad [4]$$

and t_p is the pump pulsewidth, L is the effective crystal length, L_c is the cavity length, R is the mirror reflectivity, 2a is the round trip cavity loss, P_{th}/P_{noise} is the power gain taken to be 10^{12} and

$$k = 8\pi^2 d_{eff}^{\,2} / n_p\, n_s\, n_i\, c\varepsilon_o\, \lambda_s\, \lambda_i \qquad [5]$$

where the symbols in equation [5] have their standard meaning. The calculated oscillation threshold is 19.1 mj for the 15 ns pump pulse case and 14.6 mj for the 10 ns pump pulse case. The values agree quite well with the experimental values shown in Figure 7.

Refering to Figure 1, a BBO OPO pumped by a frequency tripled Nd:YAG laser is Type I phase matchable over the entire visible and near infrared spectral regions. The OPO discussed in this paper was designed for optimum blue-green operation as indicated by the resonator mirror spectra of Figure 2. Figure 8 shows a plot of the photon conversion efficiency vs signal wavelength under modest operating conditions. A constant, nominally 30%, photon conversion efficiency was obtained from 465 nm to 540 nm, which mimics the mirror spectra of Figure 2.

The spectral linewidth of the pump laser was measured with a Fabry-Perot, (FSR = 0.85 angstroms), to be 0.33 angstroms, as shown in Figure 9, top. This corresponds to approximately 40 longitudinal modes of the 64 cm long Nd:YAG oscillator. The free-running OPO was broader than the 0.85 angstrom free spectral range of the Fabry-Perot, as no "rings" could be resolved, (Figure 9, middle). The spectral content of the OPO signal output is influenced by the spectral content of the pump laser and also by the divergence of the pump laser according to the momentum conservation considerations governing OPO operation. The spectral output of the OPO was reduced by using a 1 mm thick, quartz, intracavity etalon with both sides coated for a reflectivity of 50%, (Finesse = 4.44). The spectral content of the OPO output at 480 nm was reduced to 0.21 angstroms, as shown in Figure 9, bottom, which corresponds to approximately 7 longitudinal modes of the 3 cm long OPO resonator. The use of this intracavity etalon greatly reduced the efficiency of the OPO, to 5 - 10% of that of the free running OPO. For narrowline systems applications, an oscillator/amplifier configuration would be desirable, to restore the system efficiency.

Pulsewidth reduction effects varied with the experimental configuration used and with the conversion efficiency obtained. Most of the effects, however, were reductions on the leading and trailing edges of the pulse, as would be expected from a nonlinear process.

The BBO OPO showed no degradation in performance as the repetition rate of the pump laser was increased from 2 Hz to 10 Hz, as shown in Figure 10. A nominal energy conversion efficiency of 30% was obtained at incident pump intensities above approximately 100 MW/cm^2, regardless of repetition

rate. The maximum UV average pump power used was 0.9 watts at 10 Hz which yielded an average power of 0.27 watts at 480 nm.

No surface or bulk damage of the BBO crystals was experienced at the operating levels used as long as the crystals were inclusion free. In the earlier imported samples that were plagued with inclusions, bulk damage did occur. Figure 11 shows bulk damage at an inclusion under 25x and 100x magnification. The damage occurred at an incident pump intensity of 93 MW/cm^2, which corresponds to 1.4 J/cm^2 for a 15 ns pulsewidth.

The MgF_2 antireflection crystal coatings and the dielectric resonator mirror coatings held up well under single pass pumping and also under double pass, 15 ns pulsewidth pumping conditions. These coatings did experience cumulative damage when a double pass, 10 ns pulsewidth pumping conditions was employed.

CONCLUSION

We have constructed and characterized a pulsed beta-barium borate optical parametric oscillator pumped by a frequency tripled Nd:YAG laser. An energy conversion efficiency of 30% to 480 nm has been obtained. Pulse energies of 29 mj and average powers of 0.27 watts have been achieved. Output linewidth narrowing to 0.21 angstroms has been demonstrated. The beta-barium borate optical parametric oscillator shows great promise as a robust source of tunable radiation in the visible and near infrared spectral regions, for both high energy and high power applications.

REFERENCES

1. C. Chen, Y. X, Fan, R. C. Eckardt, and R. L. Byer, "Recent developments in barium borate", SPIE Proc. 684, (1987), pp. 12-20.

2. L. K. Cheng, W. R. Bosenberg, and C. L. Tang, "Broadly tunable optical parametric oscillation in β-BaB_20_4", Appl. Phys. Lett. 53 (1988) pp. 175-177.

3. H. Komine,"Optical parametric oscillation in a beta-barium borate crystal pumped by a XeCl excimer laser", Opt. Lett. 13 (1988) pp. 643-645.

4. W. R. Bosenberg, L. K. Cheng, and C. L. Tang, "Ultraviolet optical parametric oscillation in β-BaB_20_4", Appl. Phys. Lett. 54 (1989) pp. 13-15.

5. M. Ebrahimzadeh, A. Henderson, and M. Dunn, "An Excimer-Pumped β-BaB_20_4 Optical Parametric Oscillator Tunable from 354 nm to 2.370 mm", IEEE J. Quant. Electr. 26 (1990) PP. 1241-1252.

6. K. Kato, Parametric Oscillation in LiB_30_5 Pumped at 0.532 mm", IEEE J. Quant. Electr. 26 (1990) pp. 2043-2045.

7. Y. Wang, Z. Xu, D. Deng, W. Zheng, X. Liu, B. Wu, and C. Chen, "Highly efficient visible and infrared β-BaB_2O_4 optical parametric oscillator with pump reflection", Appl. Phys. Lett., 58, (1991) pp.1461-1463.

8. D. Eimerl, L. Davis, S. Velsko, E. K. Graham, and A. Zalkin, "Optical, mechanical, and thermal properties of barium borate", J. Appl. Phys. 62 (1987) pp.1968-1983.

9. W. R. Bosenberg, W. S. Pelouch, and C. L. Tang, High efficiency and narrow-linewidth operation of a two-crystal beta-barium borate optical parametric oscillator", Appl. Phys. Lett. 55 (1989) pp. 1952-1954.

10. S. J. Brosnan and R. L. Byer, "Optical Parametric Oscillation Threshold and Linewidth Studies", IEEE J. Quant. Electron. QE-15 (1979) pp. 415-431.

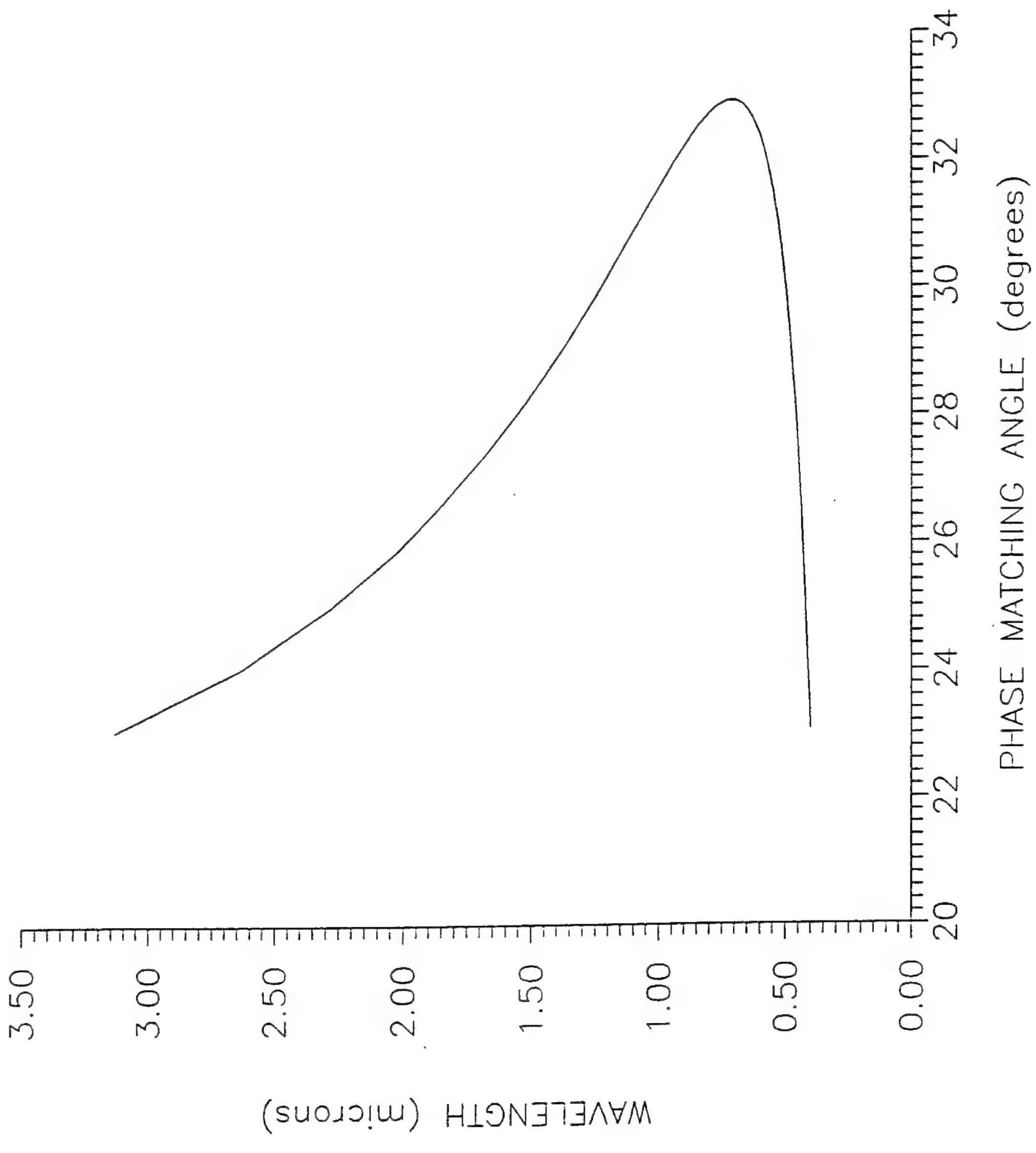

Figure 1. Calculated tuning curve for a Type I BBO OPO pumped at 354.7 nm.

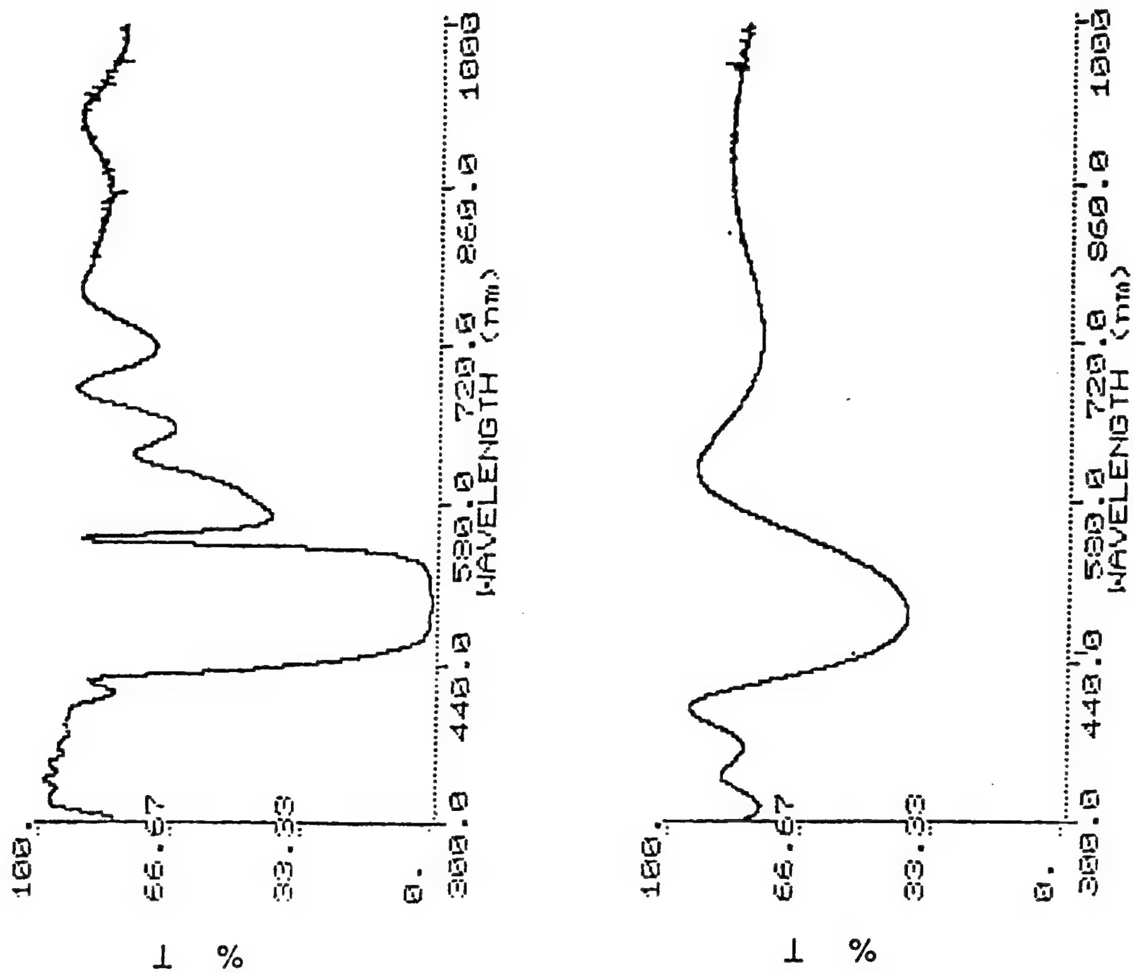

Figure 2. OPO resonator mirror reflectance/transmittance spectra.

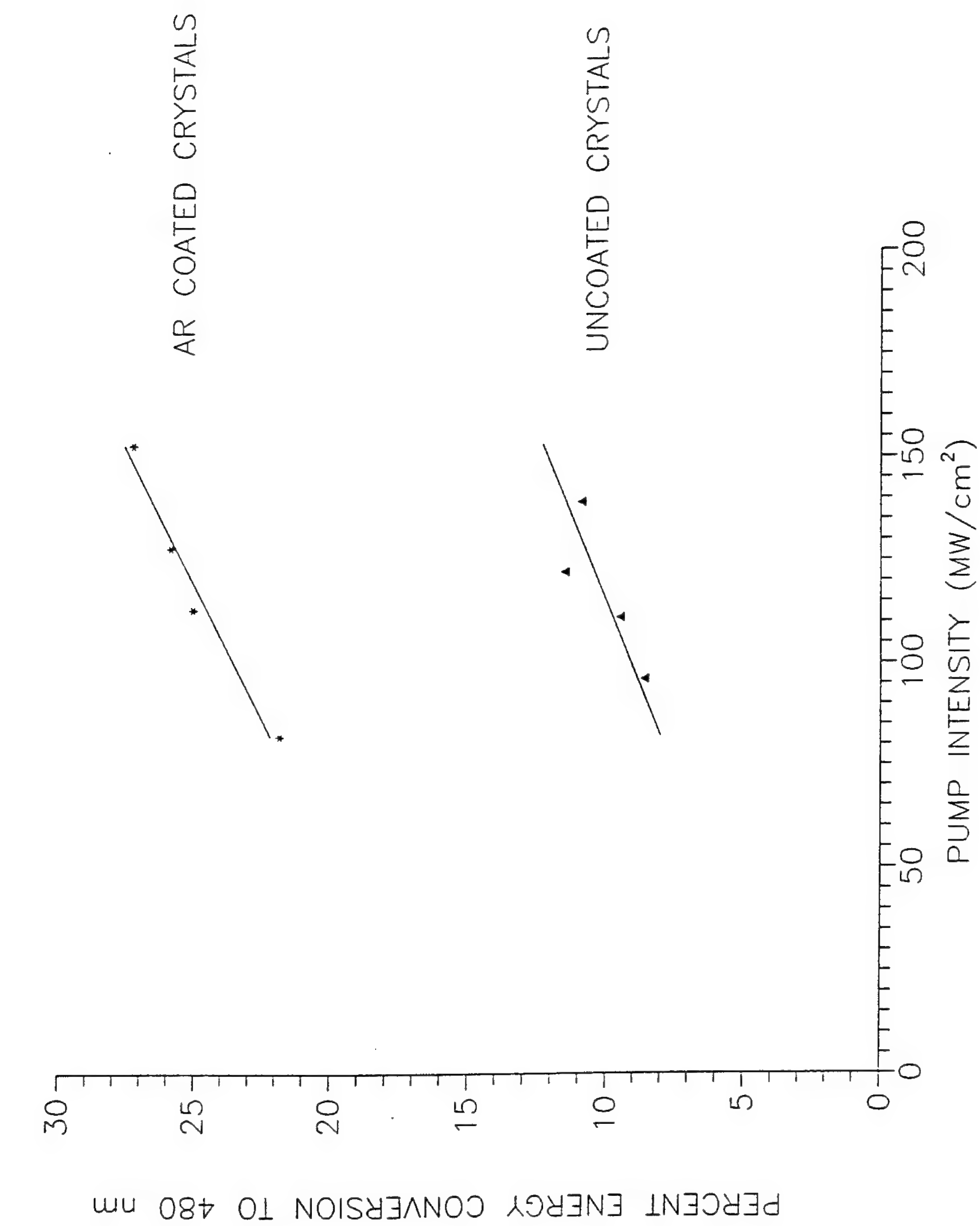

Figure 3. Percent energy conversion to 480 nm as a function of incident pump intensity. Conditions: Double pass, 10 ns pump pulse duration, crystal coatings as indicated.

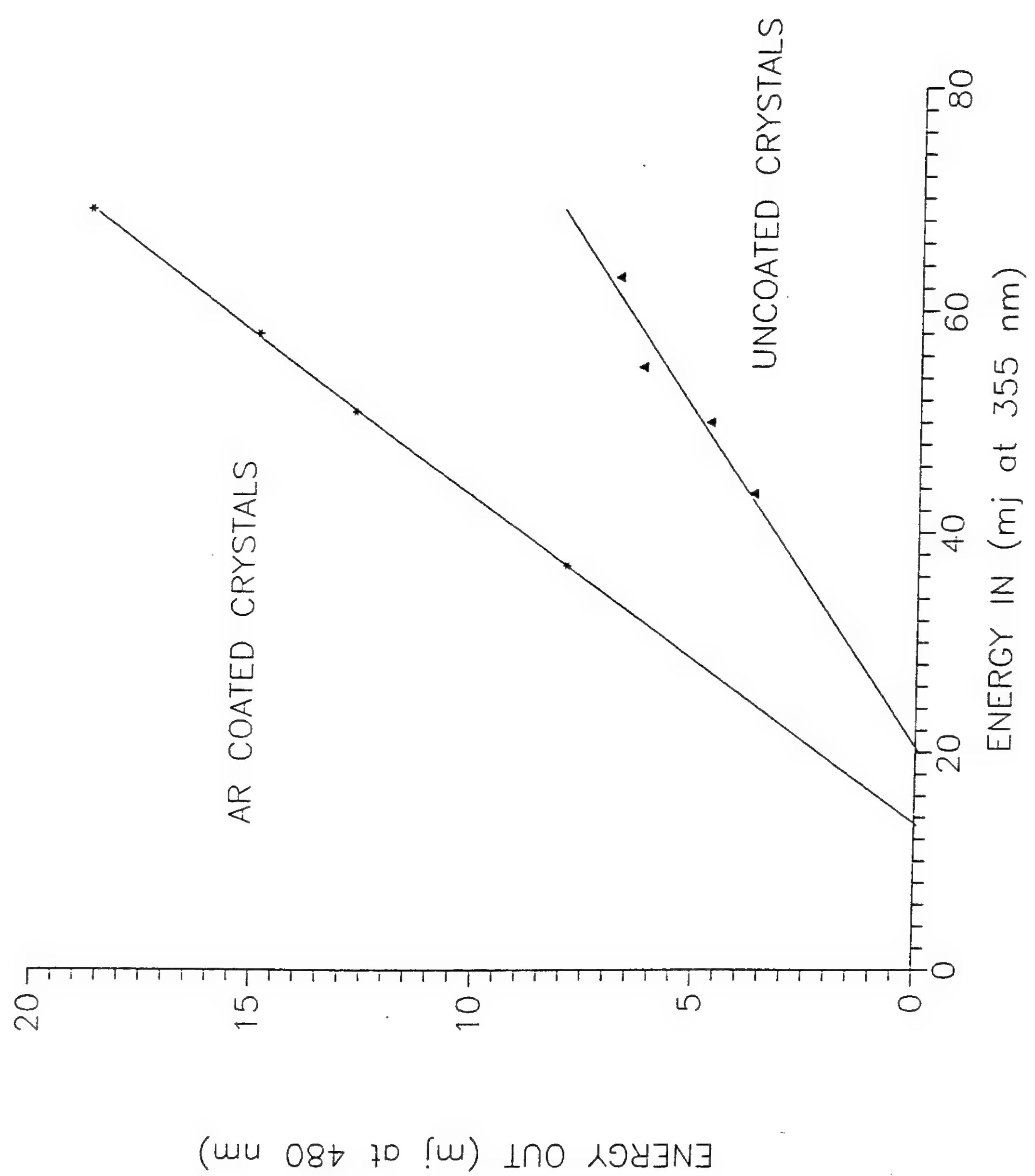

Figure 4. Output energy at 480 nm vs pump energy.
Conditions: Double pass, 10 ns pump pulse duration, crystal coatings as indicated.

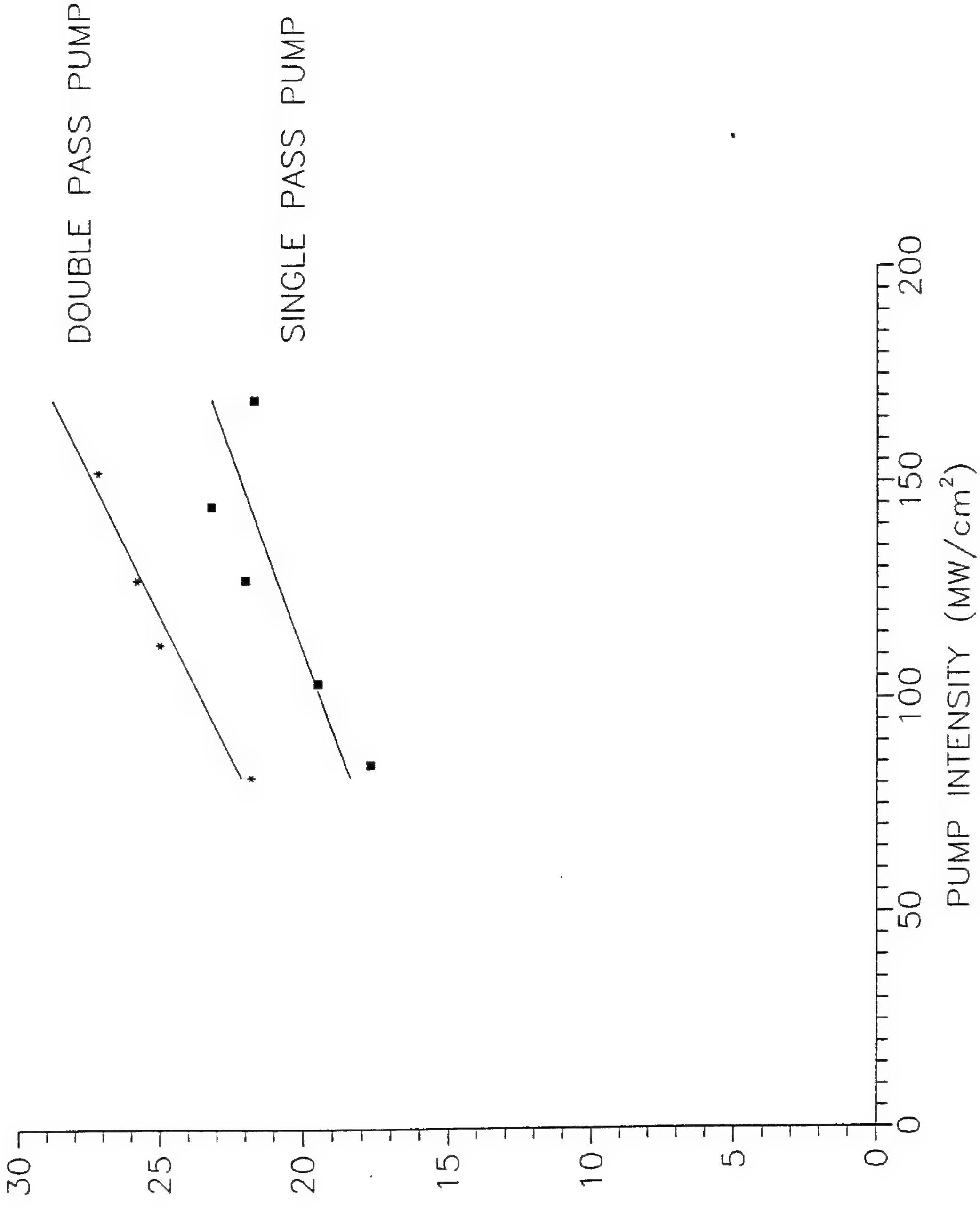

Figure 5. Percent energy conversion to 480 nm as a function of incident pump intensity. Conditions: 10 ns pump pulse duration, AR coated crystals, pump configuration as indicated.

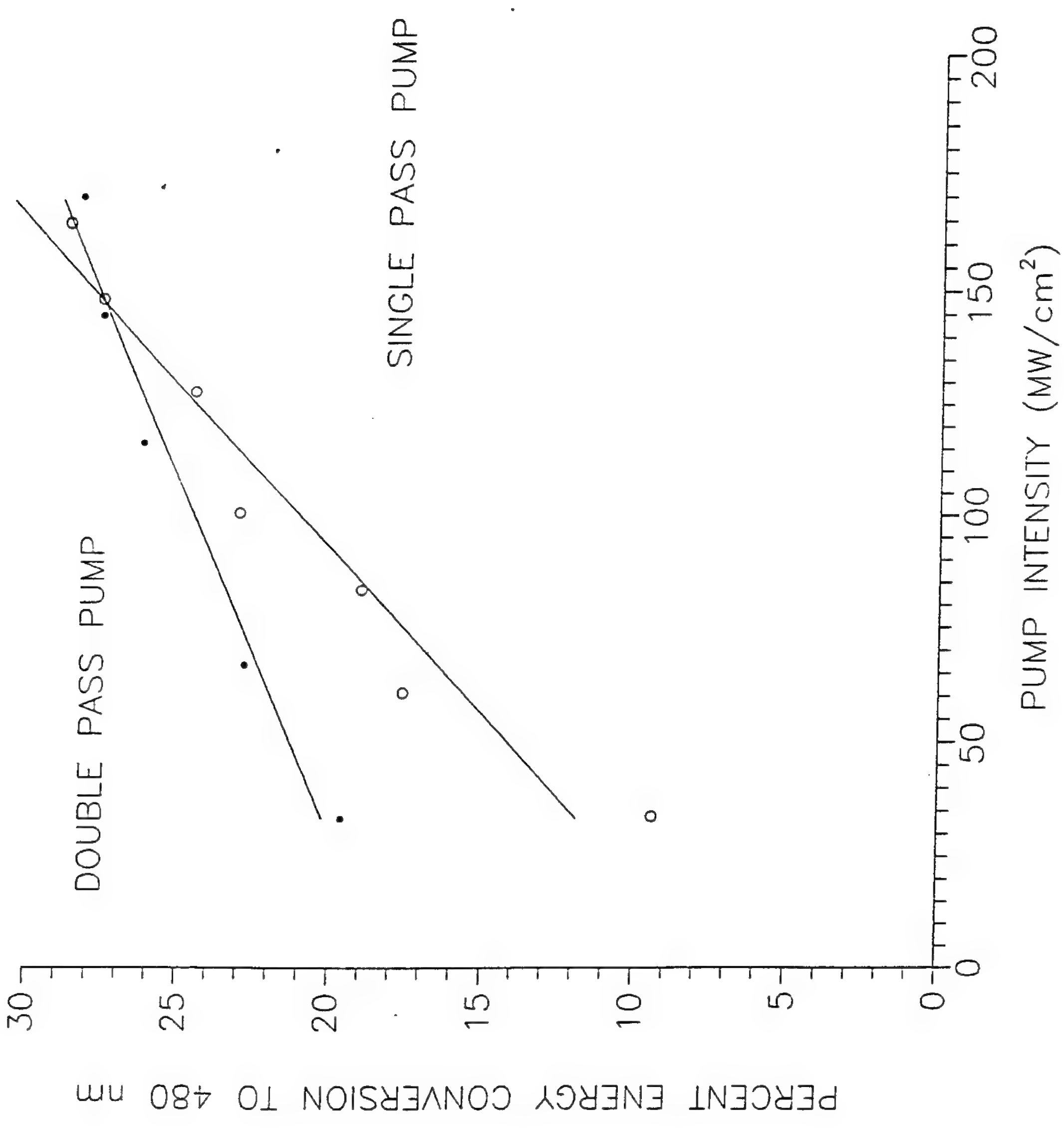

Figure 6. Percent energy conversion to 480 nm as a function of incident pump intensity.
Conditions: 15 ns pump pulse duration, AR coated crystals, pump configuration as indicated.

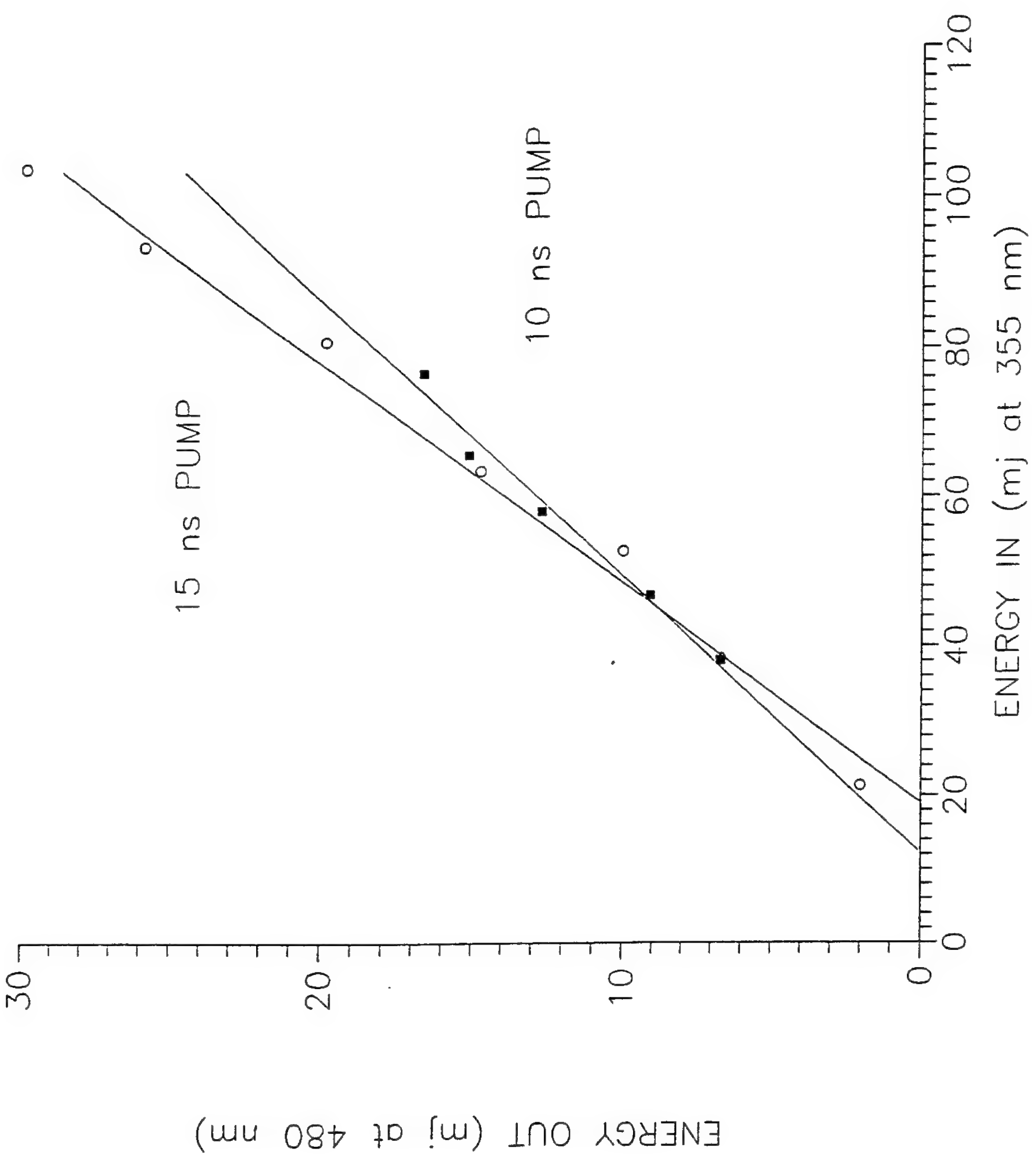

Figure 7. Output energy at 480 nm vs pump energy.
Conditions: Single pass pump configuration, AR coated crystals, pump pulse duration as indicated.

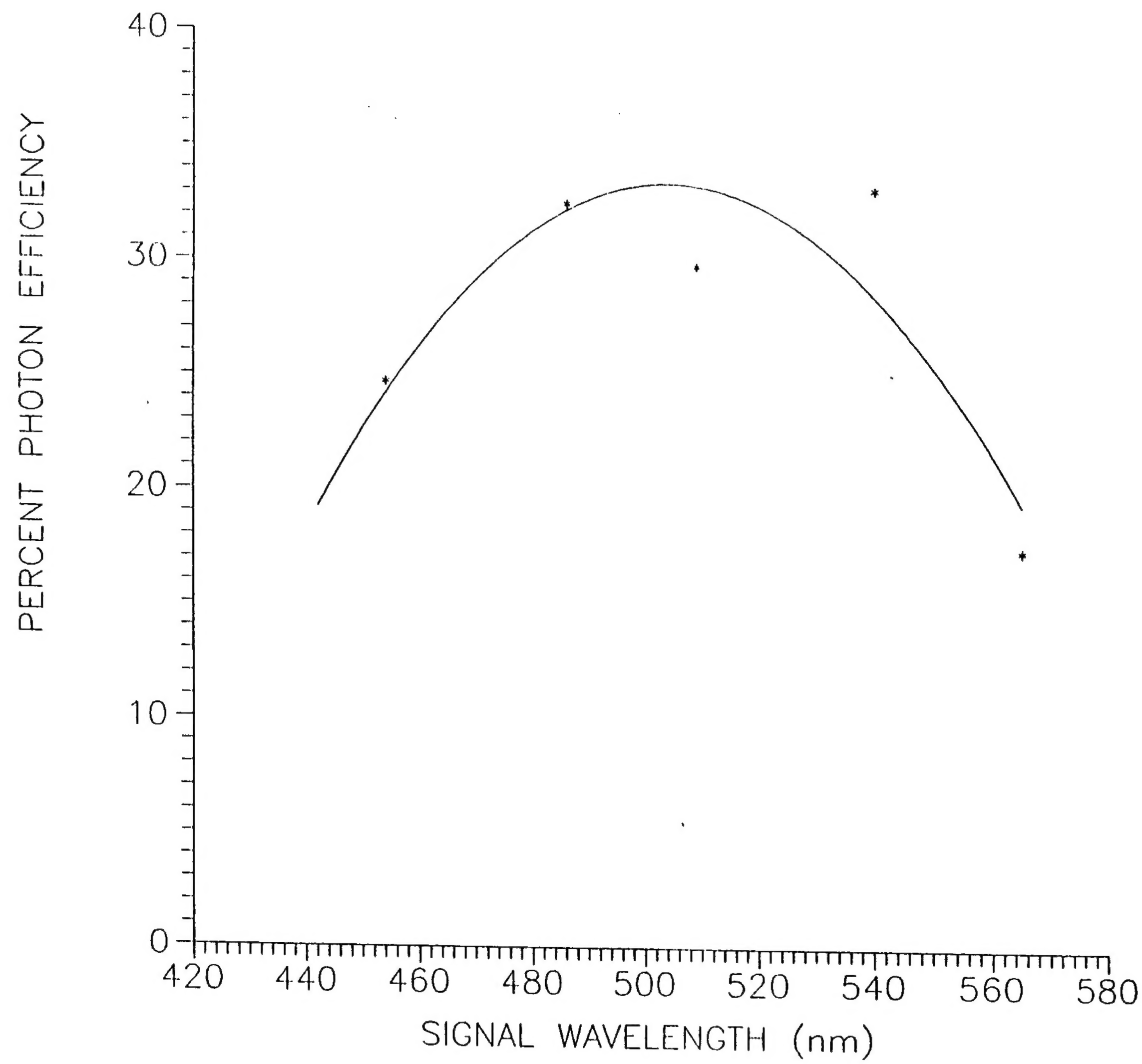

Figure 8. Photon conversion efficiency as a function of output signal wavelength.
Conditions: Double pass, 10 ns pump pulsewidth, AR coated crystals, 100 MW/cm^2 incident intensity.

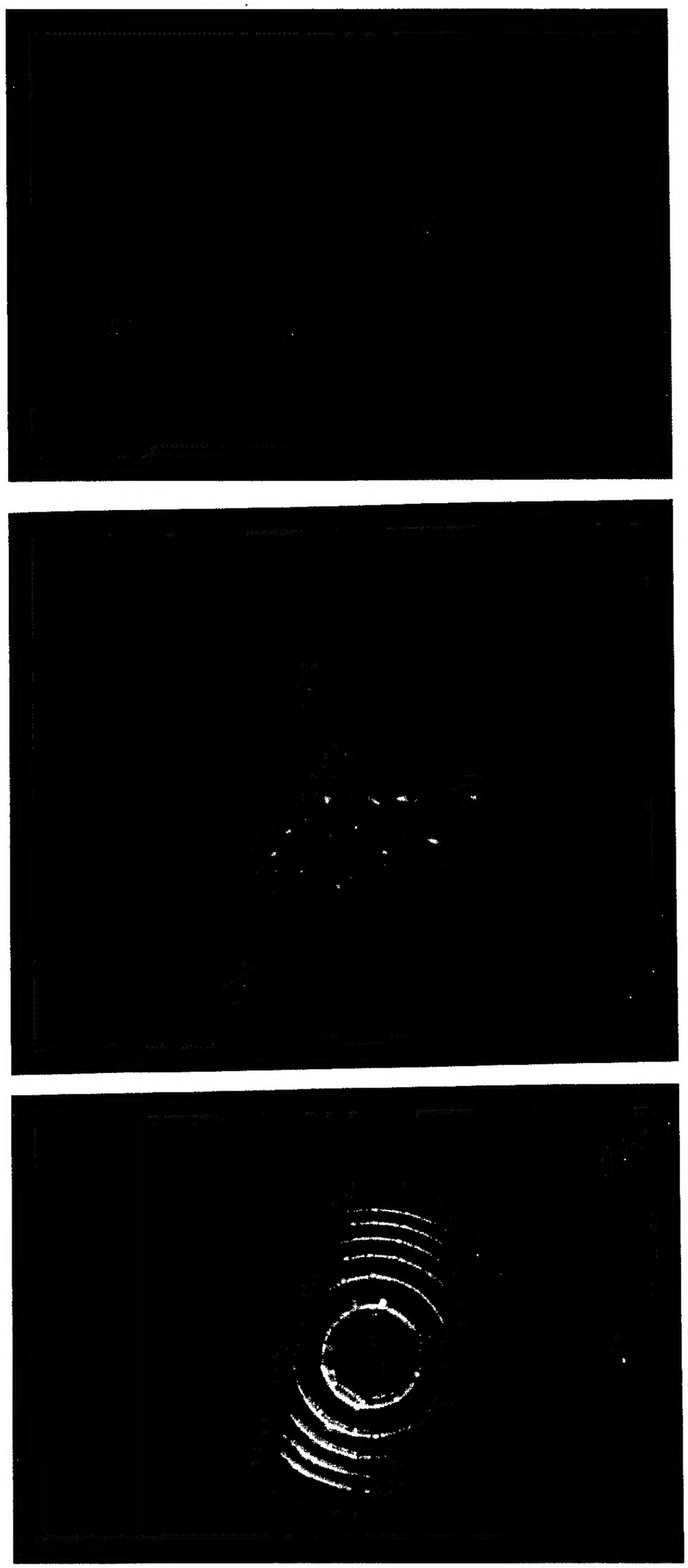

Figure 9. Fabry-Perot, (FSR = 0.85 angstroms), traces of top: second harmonic of the Nd:YAG pump laser - bandwidth = 0.33 angstroms, middle: free running OPO - bandwidth > 0.85 angstroms, and bottom: OPO with 1 mm, F=4.44, intracavity etalon - bandwidth = 0.21 angstroms.

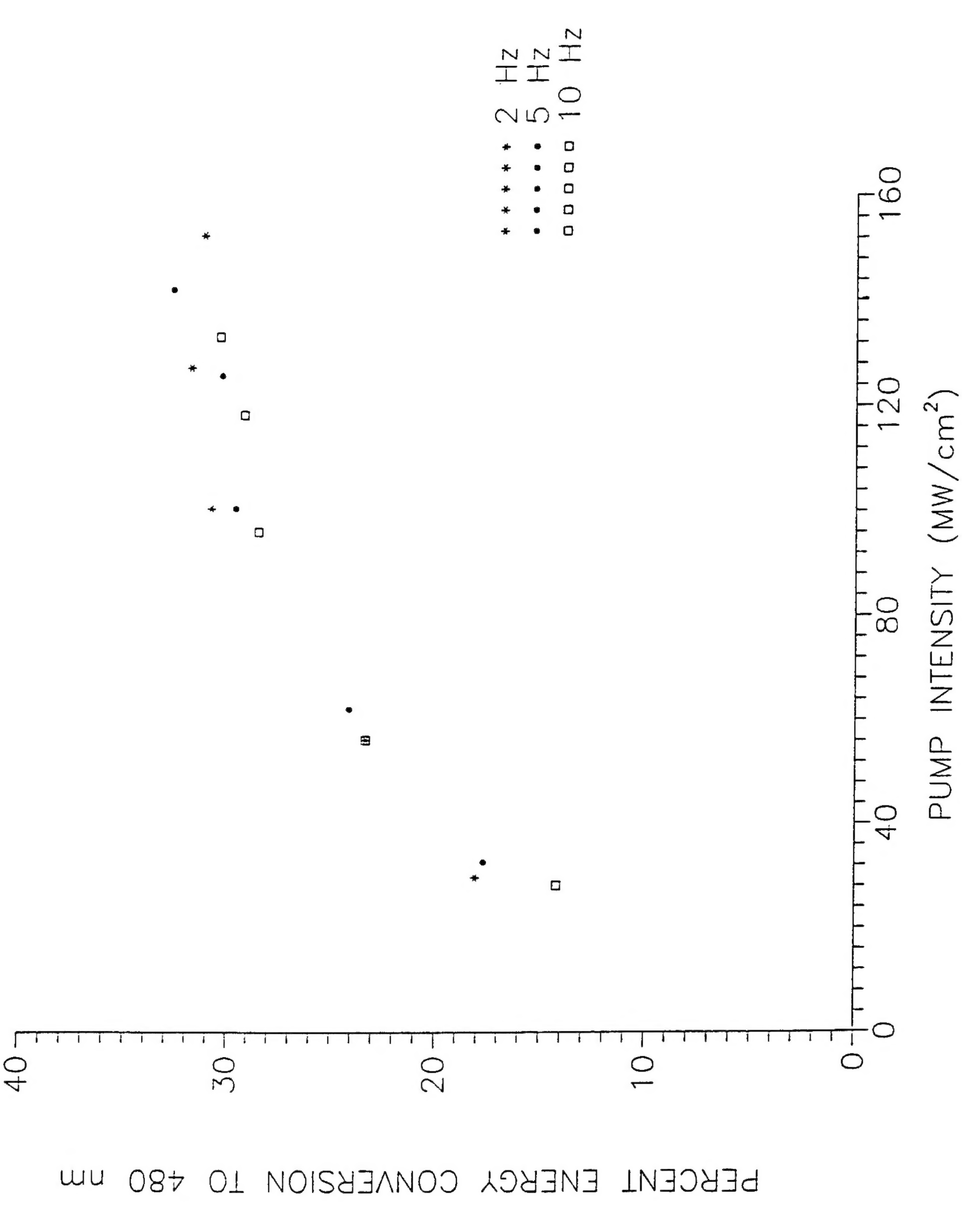

Figure 10. Percent energy conversion to 480 nm as a function of incident pump intensity.
Conditions: Double pass, 15 ns pump pulse duration, AR coated crystals, repetition rate as indicated.

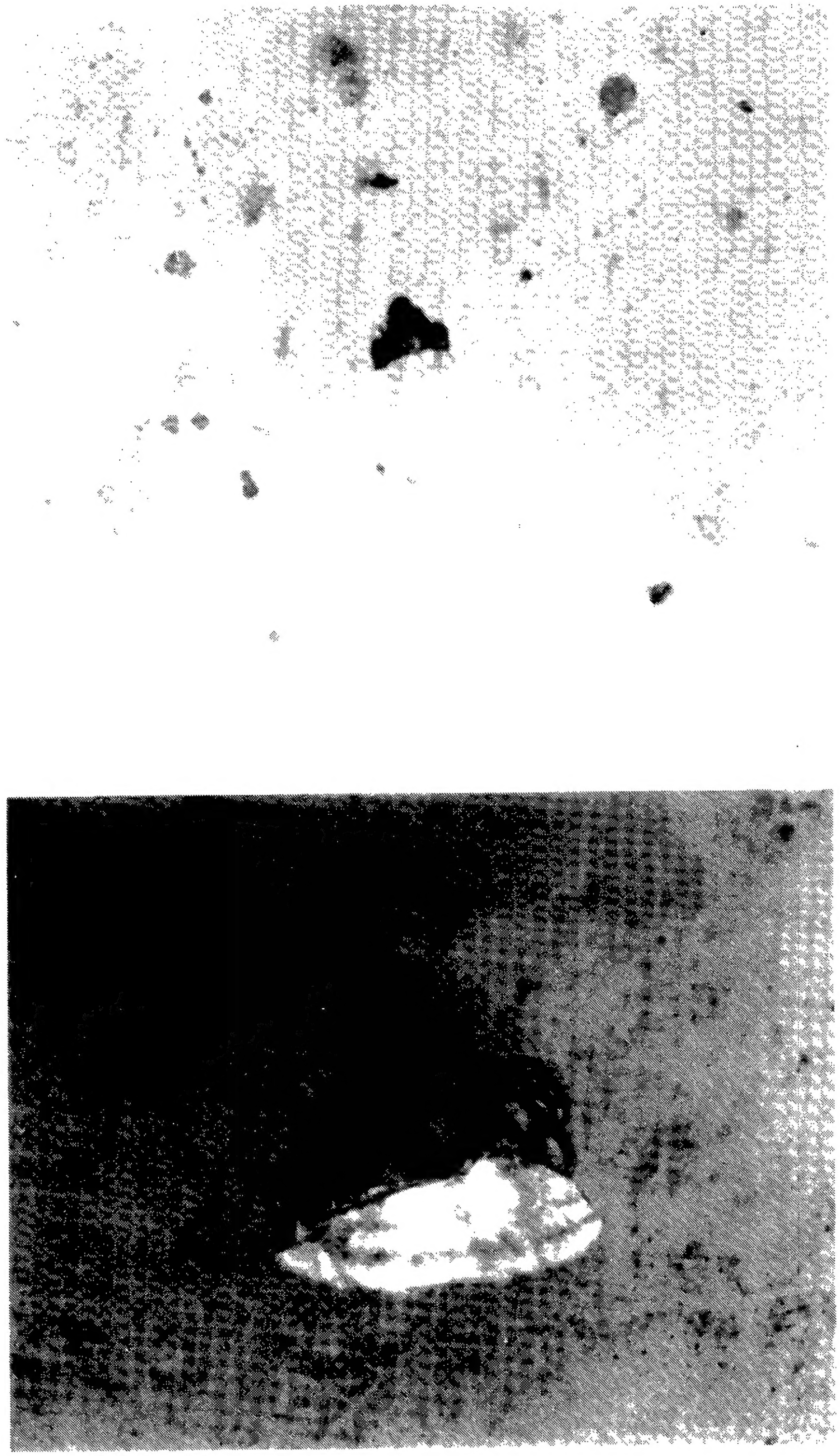

Figure 11. Example of bulk optical damage of BBO at an inclusion site at 25x and 100x magnification.